Lower Grade Waste Heat Workshop

December 13 - 14, 2016
San Francisco, CA

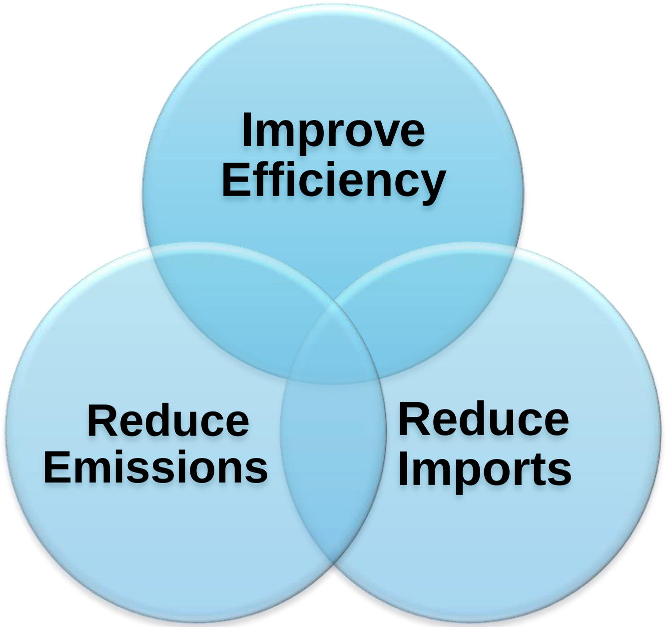
Joseph King
Program Director

ARPA-E Authorizing Legislation

Mission: To overcome long-term and high-risk technological barriers in the development of energy technologies

Goals: Ensure America's

- Economic Security
- Energy Security
- Technological Lead in Advanced Energy Technologies

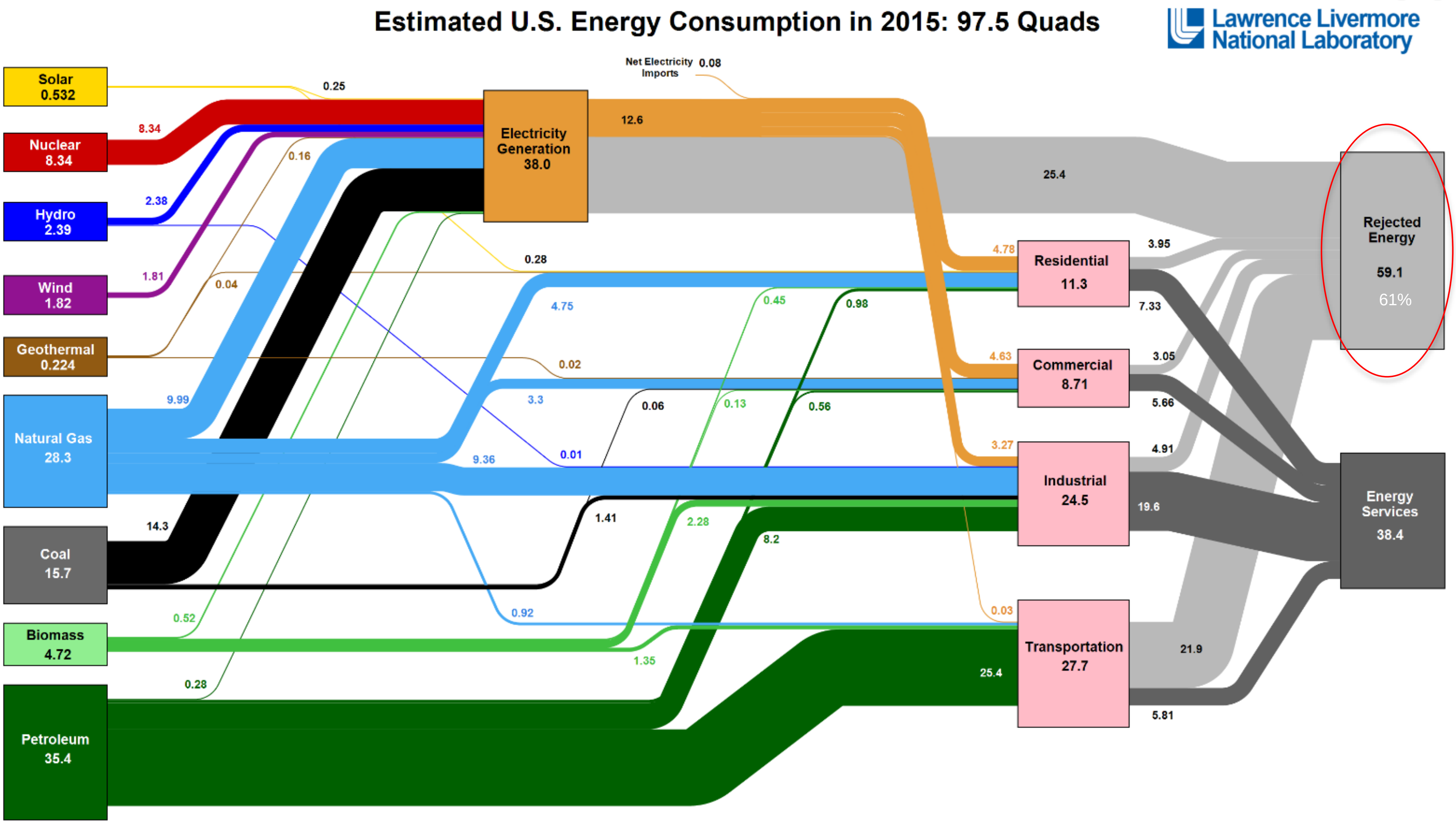


Core Maxim

If it works…

will it matter?

The Opportunity



Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

CHANGING WHAT'S POSSIBLE

The Opportunity

The amount of waste heat in Quadrillion Btu's (Quad or [Q]), that has been characterized (source, temperature) in the open literature.

Sector	Characterized Waste Heat [Q]	Total Waste Heat [Q]	% Characterized	Estimated Work Potential* [Q]
Power Generation	23.1	25.4	91%	3.2
Industrial	1.6	4.9	33%	2.1
Transportation	17.2	21.9	78%	6.7
Buildings	0.0	7.0	0%	Unknown**
TOTAL	41.9	59.2	71%	12.0

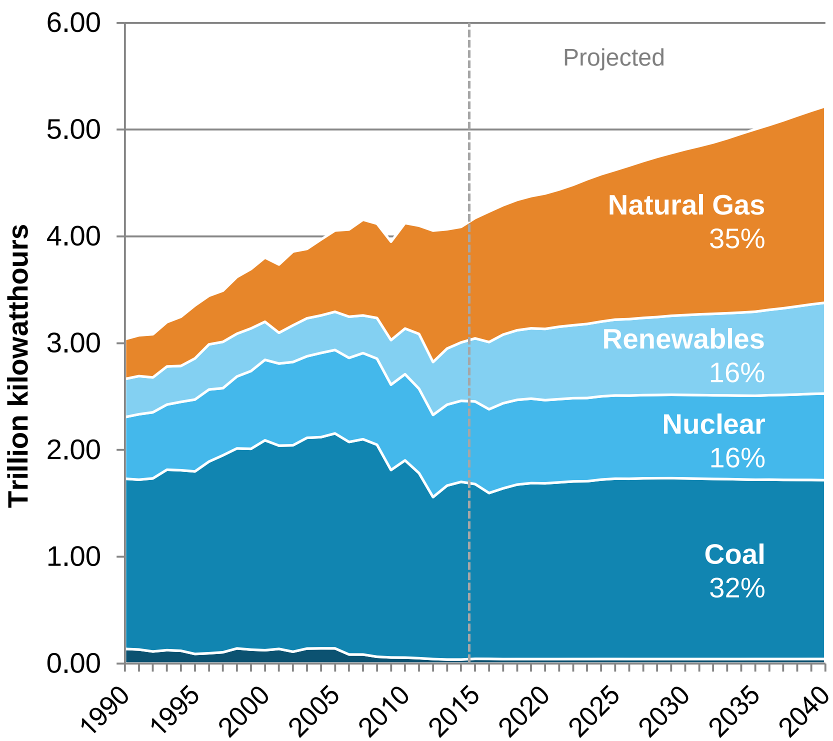
*Work potential estimates were calculated using the characterized waste heat data and then scaled up to project the work potential for the entire sector. The implicit assumption is that the distribution of waste heat in the characterized subset is representative of the full sector; this is likely to give an over estimate of the work potential in each sector.

**Because the building sector waste heat sector has not been well characterized in the literature, it is not possible to estimate its work potential accurately. However, most waste heat is likely to come from lower temperature sources like exhaust streams from HVAC and dryer systems, mechanical systems and lighting.

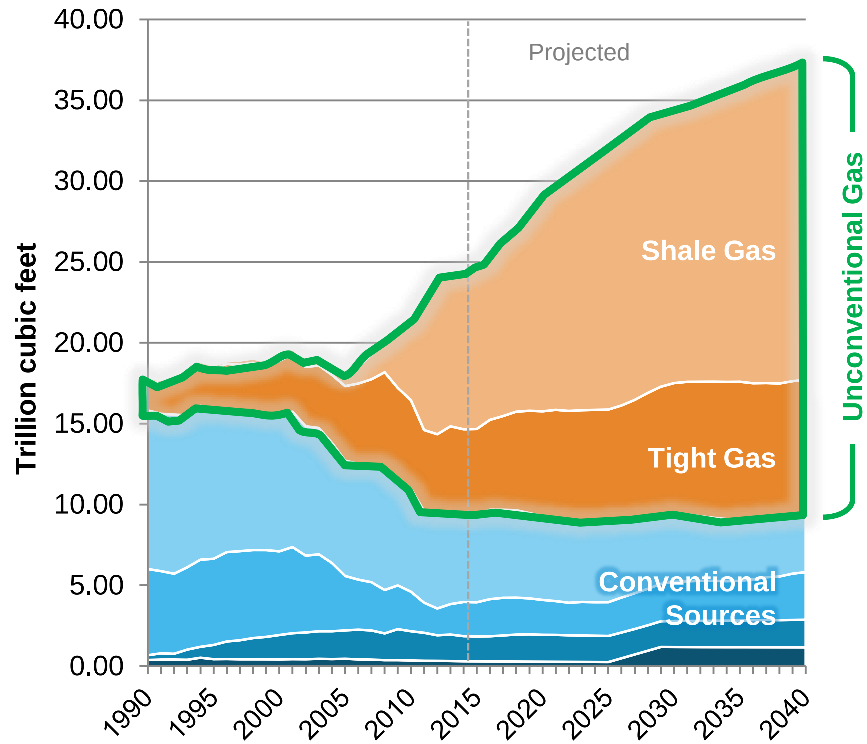
Projected Energy Growth 25 Years

Rapid growth in domestic oil and gas production has been driven by advances in horizontal drilling and hydraulic fracturing, allowing the U.S. to tap vast unconventional gas reserves; by 2035, natural gas is expected to surpass coal as the largest fuel burned to generate electricity

Electricity Generation by Fuel, 1990-2040



U.S. Dry Natural Gas Production, 1990-2040



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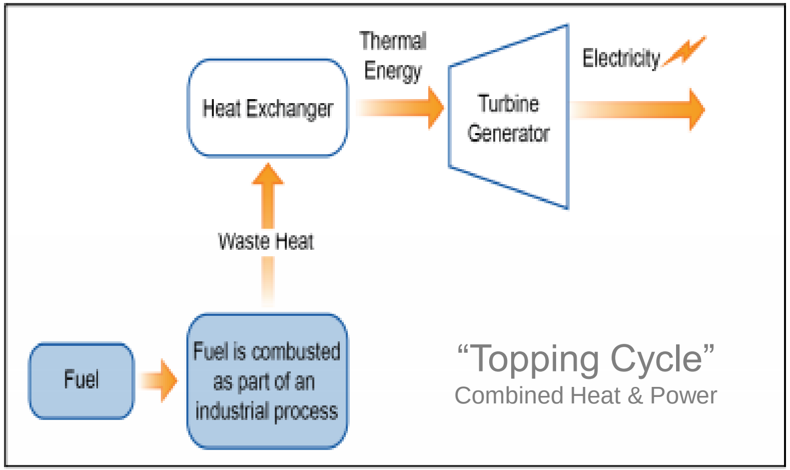
Source: U.S. Energy Information Administration Annual Energy Outlook

Common Waste Heat Conversion – Gold Standard
(Electrical Power Generation)

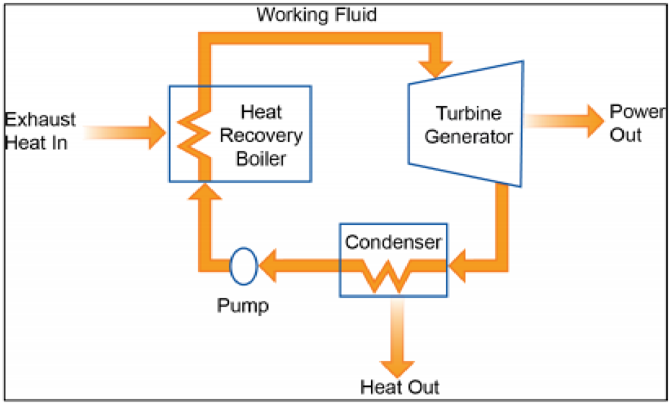
• Industrial waste heat available at a temperature sufficient for power generation (WHP) with today's technologies (*i.e.*, >500ºF [260ºC]) are estimated to be between 0.6 to 0.8 Quads (or 6,000 to 8,000 megawatts of electric generating capacity)[1] on a national basis.[2]

• Nonindustrial applications, such as exhaust from natural gas pipeline compressor drives and landfill gas engines, represent an additional 1,000 to 2,000 MW of power capacity, for a total of seven to ten gigawatts or 0.7 to 1 Quad.

• Most common (and demonstrated) methods for waste heat conversion are all Rankine variants:
- Steam Rankine Cycle (SRC)
  - > 550ºF (288ºC)
- Organic Rankine Cycle (ORC)
  - > 300ºF (149ºC)
  - Organic working fluid
- Kalina Cycle
  - 200ºF-1000ºF (93 – 538ºC)
  - Water-ammonia working fluid
  - 15-25% more efficient than ORCs



Waste Heat to Power Diagram



Rankine Cycle Heat Engine

1. Based on a range of net generation efficiencies of 20 to 30 percent and annual load factors of 50 to 85 percent;
2. Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery, T. Hendricks, Pacific Northwest National Laboratory, W. Choate, BCS Incorporated, Report to U.S. DOE Industrial Technologies Program, November 2006; Waste Heat Recovery in Industrial Facilities: Opportunities for Combined Heat and Power and Industrial Heat Pumps. EPRI, Palo Alto, CA: 2010; Waste Heat Recovery: Technology and Opportunities in the United States, Report for U.S. DOE, BCS, Incorporated, March 2008

Total Cost to Install Waste Heat Process Systems

- Costs include:
  - waste heat recovery equipment (boiler or evaporator)
  - power generation equipment (SRC, ORC, or Kalina cycle)
  - power conditioning and interconnection equipment
  - installed costs of Rankine cycle power systems (steam, ORC or Kalina) are fairly similar
- Soft costs would include:
  - designing
  - permitting and
  - constructing the system.
- Additional assumptions and considerations:
  - Representative costs shown represent a range of project sizes (< 400 kW to > 5 MW) and site complexity
  - Capital costs
    - amortized over 10 years based on a 15% cost-of-capital
    - 7,500 annual operating hours (312.5 days)
  - Operation and maintenance (O & M) are relatively low
  - There are no fuel costs for true WHP projects

Waste Heat to Power Cost Comparison

Cost Component	
Installed Costs, $/kW	$2,000 - $4,000
WHP Generating Costs	
Amortized Capital, $/kWh	$0.055 - $0.125
O&M Costs, $/kWh	$0.005 - $0.020
Total Power Cost, $/kWh	**$0.060 - $0.125**

Source: *ICF International estimates, 2012*

U.S. EPA Combined Heat and Power Partnership (CHP) “Waste Heat to Power Systems” document 2015-07

Cost Considerations Per Technology

Options for Heat Recovery via Power Generation

Thermal Conversion Technology	Temperature Range	Typical Sources of Waste Heat	Capital Cost
Traditional Steam Cycle [a]	M,H	Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces.	\$1100-1,400/kW[f]
Kalina Cycle [d]	L,M,	Gas turbine exhaust, boiler exhaust, cement kilns	\$1100-1,500/kW[f]
Organic Rankine Cycle [c,e]	L,M	Gas turbine exhaust, boiler exhaust, heated water, cement kilns	\$1,500-3,500/kW[f]
Thermoelectric Generation [b]	M-H	Not yet demonstrated in industrial applications	\$20,000-30,0000/kW[b]
Piezoelectric generation [b]	L	Not yet demonstrated in industrial applications	\$10,000,000/kW[b]
Thermal Photovoltaic	M-H	Not yet demonstrated in industrial applications	N/A

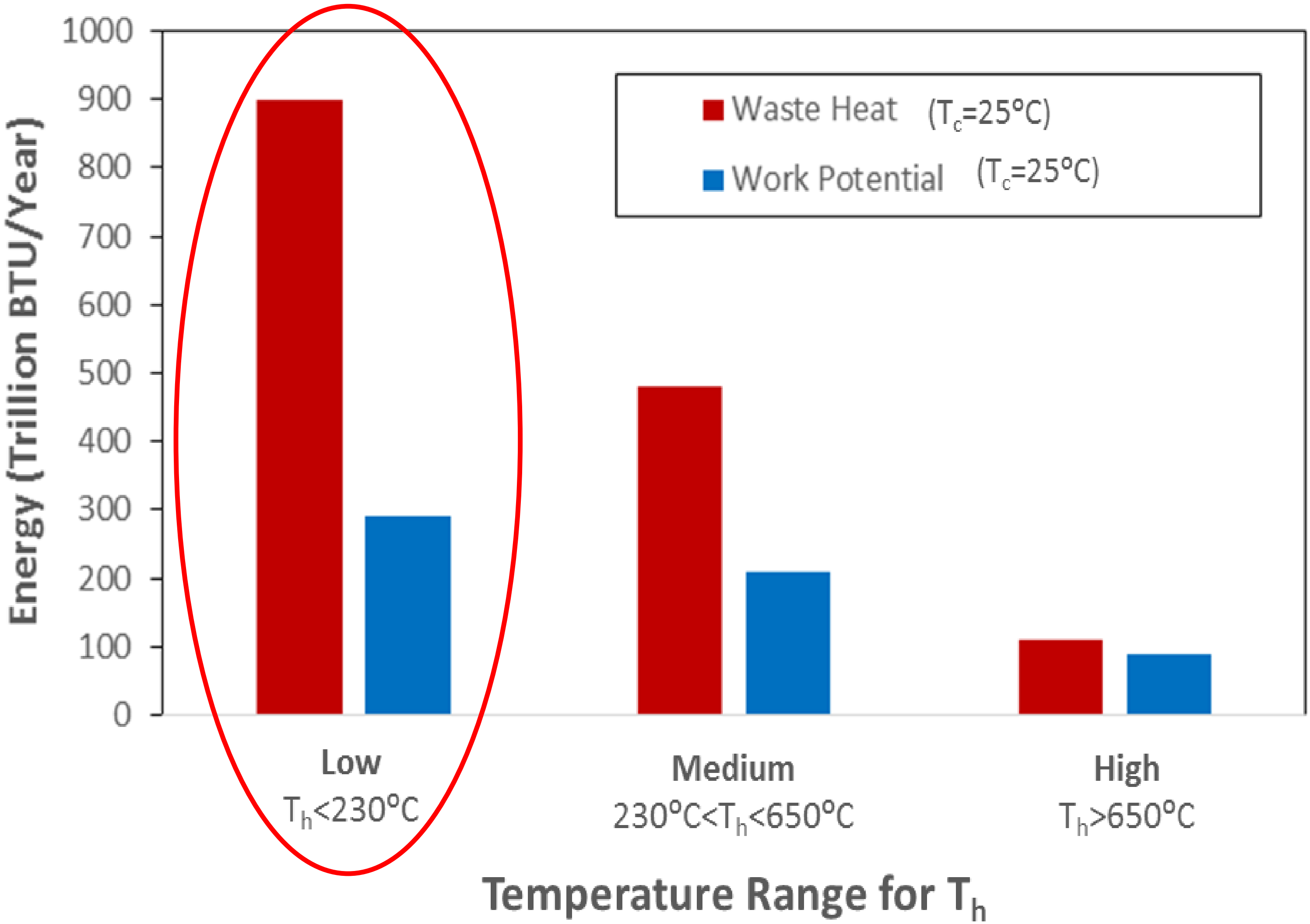
a. Sean Casten, 2003. Update on US Steam Turbine technology, Presented to Canadian District Energy Association 8th Annual Conference June 20th 2003.
b. BCS, Inc., Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery
c. Daniel Duffy, "Better Cogeneration through Chemistry: the Organic Rankine Cycle
d. based on cement kiln waste heat recovery project economics. Mark Mirolli, "The Kalina Cycle for Cement Kiln Waste Heat Recovery Power Plants." Cement Industry Technical Conference, 2005. 15-20 May 2005.
e. "Organic Rankine Cycle for Electricity Generation. http://www.stowa-selectedtechnologies.nl
f. Paul Cunningham, "Waste Heat/ Cogen Opportunities in the Cement Industry" Cogeneration and Competitive Power Journal. Vol 17, No 3 p. 31-50

The Provocation

"Comparison of total work potential from different waste heat sources showed that the magnitude of low-temperature waste heat is sufficiently large that it should not be neglected in pursuing RD&D opportunities for waste heat recovery."*

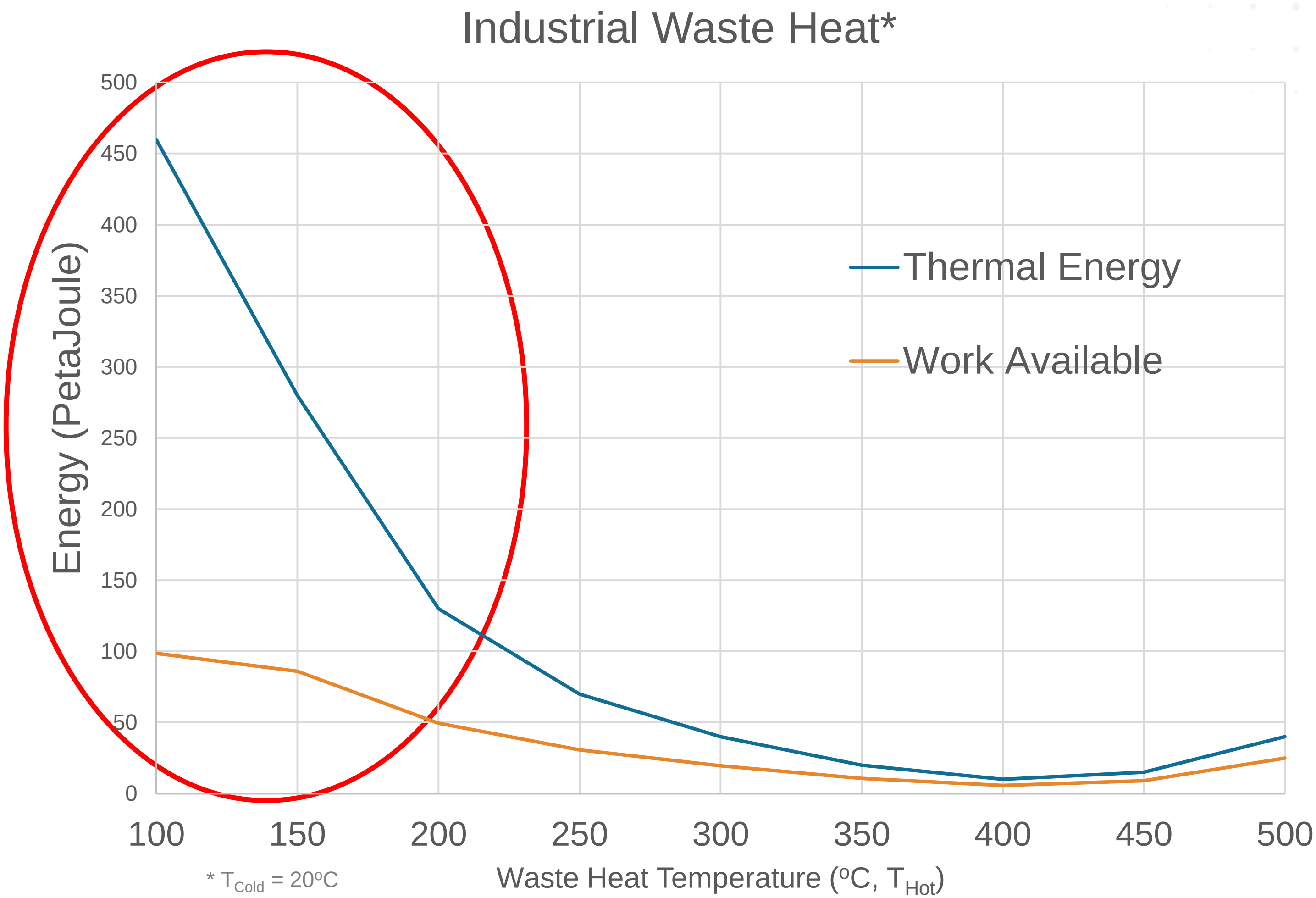
*Source - U.S. Department of Energy Industrial Technologies Program report: "Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

The Big Opportunity Is In Lower Quality Heat



Source - U.S. Department of Energy Industrial Technologies Program report: "Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

Waste Heat versus Exergy - Is the Climb Worth the View?



Source - U.S. Department of Energy Industrial Technologies Program report: "Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

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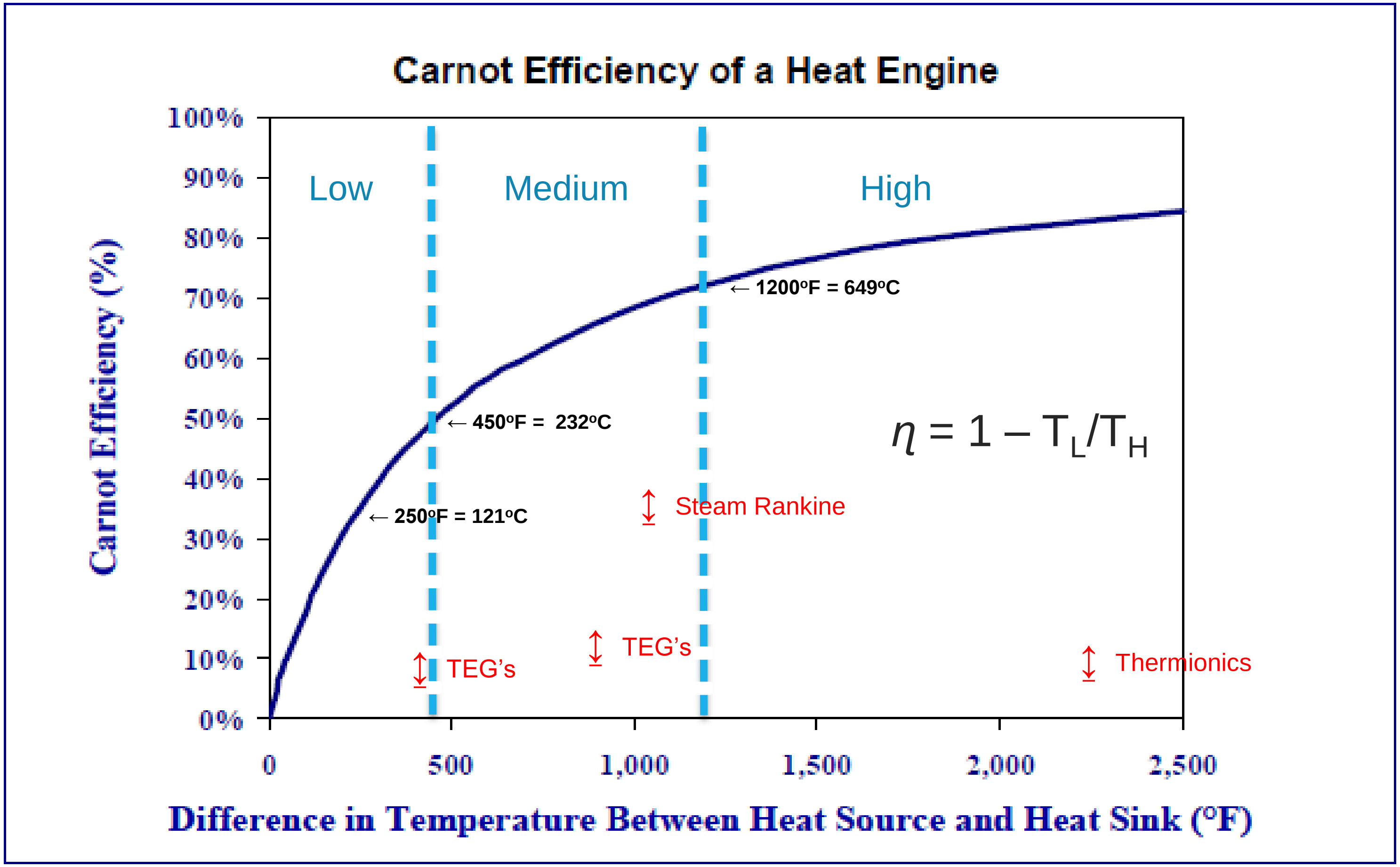
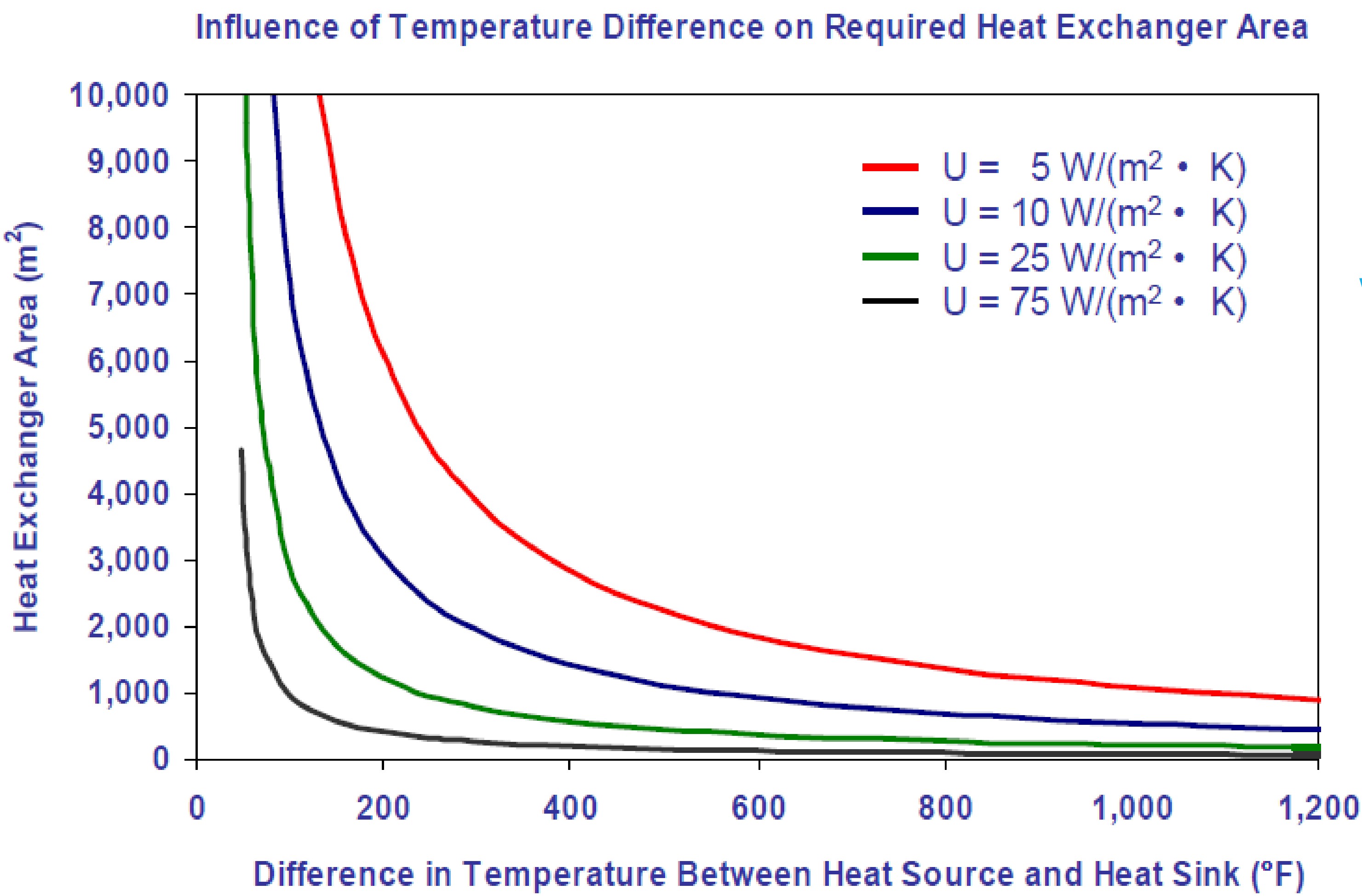
Maximum Theoretical Efficiency



Variation of Carnot Efficiency of Heat Engines as a Function of ΔT

Source - U.S. Department of Energy Industrial Technologies Program report:
"Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

Limitations On Effective Heat Transfer



Where: $Q = UA\Delta T$
(W or Btu/s)

Q = heat transfer rate
U = heat transfer coefficient
A = surface area of the heat exchanger
ΔT = temperature difference between the two streams

The Influence of Source and Sink Temperature (ΔT) on Required Heat Exchanger Area

Source - U.S. Department of Energy Industrial Technologies Program report: "Waste Heat Recovery – technical and Opportunities in U.S. Industry, prepared by BCS, Inc. March 2008"

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This figure graphs the surface area (m^2) required for recovering 10 million Btu/hr from a gaseous exhaust stream with a mass flow rate of 5 million lbs/hr by transfer to liquid water flowing at 1 ft^3/s. Calculated using estimated log mean temperature difference for ΔT.

Operational Cost Comparison: TEG$_{Example}$

A cost comparison of competing power generation technologies (LeBlanc et al. 2014)

Application Temperature	Power Generation Technology	System Cost ($/W)
Low ($T_h \approx 100$ °C)	Geothermal	$4.14
	Half-Heusler Thermoelectric (Bulk $Zr_{0.25}Hf_{0.25}Ti_{0.5}NiSn_{0.994}Sb_{0.006}$)	$125.05
	Silicon Nanowire Thermoelectric	$104.18
	Chalcogenide Thermoelectric (Nanobulk $Bi_{0.52}Sb_{1.48}Te_3$)	$62.44
Medium ($T_h \approx 250$ °C)	Organic Rankine Cycle	$4.00
	Concentrating Solar Power	$3.60
	PV Target	$1.00
	Skutterudite Thermoelectric (Bulk $Yb_{0.2}In_{0.2}Co_4Sb_{12}$)	$19.02
	Half-Heusler Thermoelectric (Bulk $Zr_{0.25}Hf_{0.25}Ti_{0.5}NiSn_{0.994}Sb_{0.006}$)	$14.45
	Chalcogenide Thermoelectric (Nanobulk $Bi_{0.52}Sb_{1.48}Te_3$)	$11.92
High ($T_h \approx 500$ °C)	Nuclear	5.34
	Coal	$2.84
	Natural Gas	$0.98
	Silicide Thermoelectric (Bulk $Mg_2Si_{0.6}Sn_{0.4}$)	$5.56
	Chalcogenide Thermoelectric (Bulk $AgPb_{18}SbTe_{20}$)	$5.06
	Half-Heusler Thermoelectric (Bulk $Zr_{0.25}Hf_{0.25}Ti_{0.5}NiSn_{0.994}Sb_{0.006}$)	$4.48

Properties, materials/device efficiency, and cost for different families of thermoelectric materials

Material Family	Max ZT	Temp (°C)	Efficiency	Average Material Cost ($/kg)
Cobalt Oxide	1.4	727	12%	$345
Clathrate	1.4	727	12%	$5,310
SiGe	0.86	727	9%	$6,033
Chalcogenide	2.27	727	16%	$730
Half -Heusler	1.42	427	17%	$1,988
Skutterudite	1.5	427	18%	$562
Silicide	0.93	727	9%	$151

For Low Quality Waste Heat Source
- Need Two Orders of Magnitude Drop in System Costs

For Medium Quality Waste Heat Source
- Need Slightly Greater than One Order of Magnitude Drop in System Costs

For High Quality Waste Heat Source
- Need a 2 to 5-fold Drop in System Costs

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LeBlanc, S., Yee, S. K., Scullin, M. L., Dames, C. & Goodson, K. E. *Renewable and Sustainable Energy Reviews*, **32**, (2014) 313- 327; Seshadri Group (2013) Energy Materials Datamining. U.C Santa Barbara Materials Research Laboratory; DOE Pre-Decisional Draft (QTR Chapter 8) "*Thermoelectric Materials, Devices, and Systems: Technology Assessment*" February 13, 2015.

Agenda Review

and Workshop Flow

San Francisco Workshop Agenda Day One

Tuesday, 12/13

Time	Event
9:00 – 11:00 AM	Individual meetings with Dr. Joseph King and his technical team
11:00 – 11:45 AM	Registration and Lunch
11:45 AM - 12:00 PM	**Welcome and Introduction to ARPA-E** *Dr. Ellen Williams, Director, ARPA-E*
12:00 - 12:20 PM	**Lower Grade Waste Heat Recovery – Goals, Opportunities and Areas of Interest** *Dr. Joseph King, Program Director ARPA-E*
12:20 – 12:50 PM	**Workshop participant introductions**
12:50 – 1:15 PM	**Thermomagnetics and Multiferroics** *Guest Speaker: Prof. Bharat Jalan, University of Minnesota*
1:15 – 1:40 PM	**Rectennas** *Guest Speaker: Dr. Patrick Brady, Redwave Energy*
1:40 – 2:05 PM	**Thermoacoustics** *Guest Speaker: Prof. Robert Keolian, Pennsylvania State University*
2:05 – 2:30 PM	**Metamaterials and Material Synthesis** *Guest Speaker: Dr. Augustine Urbas, Air Force Research Laboratory*
2:30 - 2:40 PM	**Breakout 1 Overview** *Dr. Joseph King, ARPA-E*
2:40 – 3:00 PM	**Break/Networking**
3:00 – 5:00 PM	**Breakout Session 1**
5:00 PM	**Informal Networking/Dinner – Organize on Your Own**
5:30 – 8:00 PM	Individual meetings with Dr. Joseph King and his technical team

San Francisco Workshop Agenda Day Two

Wednesday, 12/14

Time	Event
7:00 – 8:00 AM	Breakfast
8:00 - 8:10 AM	**Day 1 Summary/Readout and Day 2 Objectives** *Dr. Joseph King, ARPA-E*
8:10 – 8:35 AM	**Thermoelectric Generators and Thermionics** *Guest Speaker: Prof. Mona Zebarjadi, University of Virginia*
8:35 – 9:00 AM	**Heat Transport – Capture and Rejection** *Guest Speaker: Prof. Gang Chen, Massachusetts Institute of Technology*
9:00 – 9:25 AM	**Mechanical Systems** *Guest Speaker: Prof. Todd Bandhauer, Colorado State University*
9:25 – 9:30 AM	**Breakout 2 Overview** *Dr. Joseph King, ARPA-E*
9:30 – 9:50 AM	Break/Networking
9:50 – 11:45 AM	**Breakout Session 2**
11:45 - 11:50 AM	Wrap-up
12:00 – 1:00 PM	Individual meetings with Dr. Joseph King and his technical team

What happens post-workshop?

Team: using ALL info:

- Develop proposed performance metrics
- Define program technical areas and structure

Program proposed to ARPA-E

If program approved, FOA in early-mid 2017

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Advanced Research Projects Agency • ENERGY

U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0001580

Waste Heat Devices

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Teaming List

ABB	EERE-BTO	Psikick
Amphenol Advanced Sensors	EPRI	Spruce Capital
Analog Devices Inc.	FIU	SRI International
ANL	GE Global Research/AI & Learning	Stony Brook University
Apsis Automation, LLC	IBM T.J. Watson Research Center	Syracuse University
Architectural Applications	Infineon Technologies	Telkonet
Bosch	Ingersoll-Rand	Temple Univ.
Boston University	LBNL	The Univ. of Texas at San Antonio
California State Univ. Dominguez Hills	NEEA	United Technologies Research Center
Cree Inc.	NREL	Univ. of Florida
Daikin US Corporation	ORNL	University of Michigan
DUKE ENERGY	PARC	WeatherBug Home
Ecobee Inc	Phillips	X
EcoVox, Inc.	PNNL	ZAN Compute

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Lower Grade Waste Heat Recovery Workshop
December 13-14, 2016
Hilton San Francisco Union Square
333 O'Farrell St, San Francisco, CA 94102

Tuesday, 12/13

Time	Event
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12:20 – 12:45 PM	**Guest speaker 1 Thermomagnetics and Multiferroics** *Guest Speaker: Bharat Jalan, University of Minnesota (Confirmed)*
12:45 – 1:10 PM	**Guest speaker 2 Rectennas** *Guest Speaker: Patrick Brady, Redwave Energy (Confirmed)*
1:10 – 135 PM	**Guest speaker 3 Thermoacoustic** *Guest Speaker: Robert Keolian, Pennsylvania State University (Confirmed)*
1:35 – 2:00 PM	**Guest speaker 4 Metamaterials and Material Synthesis** *Guest Speaker: Augustine Urbas, Air Force Research Laboratory (Confirmed)*
2:00 – 2:30 PM	**Break/Networking**
2:30 - 2:40 PM	**Breakout 1 Overview** *Dr. Joseph King, ARPA-e*
2:40 – 5:00 PM	**Breakout Session 1: 3 parallel breakouts** • IR Plasmonics, Rectennas, Semiconductor Diode • Magnetocaloric, Multiferroics, Thermomagnetics • Thermoacoustics, Thermochemical
5:00 PM	**Informal Networking/Dinner – Organize on Your Own**
5:30 – 8:00 PM	One-on-one Meetings with Joseph King

Workshop Team:

Technical:

Dr. Colleen Nehl,

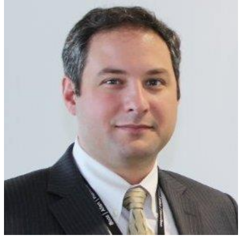
Technologist (BAH)

Mr. Geoff Short,

Lead Engineer (BAH)

Dr. Russel Ross,

Technologist (BAH)



Dr. David Brown,

ARPA-e Fellow

Administrative Support:

Nancy Hicks

Senior Event Manager (BAH)

Colby Rachfal

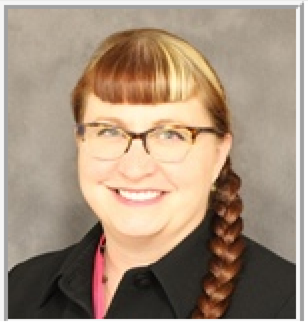
Senior Consultant (BAH)

Facilitators:

Program Directors:

Dr. Chris Atkinson currently serves as a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). His focus at ARPA-E includes improving the energy efficiency of advanced combustion devices, and energy conversion and storage systems.

Dr. Isik C. Kizilyalli currently serves as a Program Director at the Advanced Research Projects Agency – Energy (ARPA-E). Kizilyalli's focus at ARPA-E includes electrification, power electronics, high efficiency power conversion, wide bandgap semiconductors, electronic systems for extreme environments, solar PV, instrumentation for intrinsically safe nuclear energy, comminution, and enhanced geothermal systems. .



Dr. Jennifer Gerbi currently serves as a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). Her focus at ARPA-E includes improving energy efficiency and management via advanced sensing systems and storage, as well as renewable energy generation via photovoltaics.

Dr. Michael E. deSa
Expert Advisor

Dr. Michael Haney currently serves as a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). His focus at ARPA-E includes the application of integrated optics and photonics technologies for energy-efficient computing, switching, signal processing, and power conversion.

Dr. Michael Ohadi
Program Director

Thank You For Your Participation!

"As in other activities – it is far easier to start something than it is to finish it."

Amelia Earhart

Breakout Session

Why You: What You Bring

The Three Necessary Ingredients of Creative Individuals:

1. Continuing preoccupation with problems over a considerable period of time;

2. Willingness to accept vaguely defined problem statements and gradually structure them;

3. Extensive background knowledge in relevant and potentially relevant areas.

Herbert A. Simon
(1916 - 2001)

Why You: What DOE Needs From You

“*Discovery consists of seeing what everybody has seen and thinking what nobody has thought.*”

Albert Szent-Györgyi de Nagyrapolt

The Scientists Speculates, 1962

(1893-1986)

“*Creativity is just connecting things*.”

Steve Jobs

(1955-2011)